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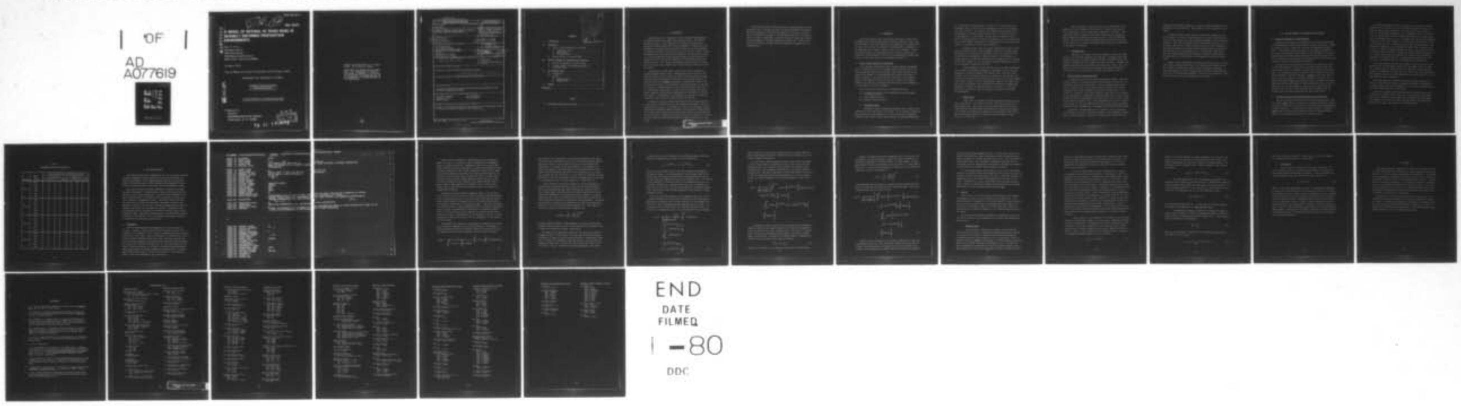

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A MODEL OF NATURAL HF RADIO NOISE IN SEVERELY DISTURBED PROPAGATION ENVIRONMENTS

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31 March 1979

Topical Report for Period 17 November 1977—31 March 1979

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A model is developed that describes the impact of severe propagation losses on the natural noise environment at high frequencies.

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TABLE

I INTRODUCTION

The performance of a communication system depends fundamentally on the signal-to-noise ratio (SNR) at the receiver output. For UHF and microwave systems, a major component of the noise is thermal noise generated internally within the receiver components; recognition of the advantages to be gained from noise reduction has led to the development of parametric amplifiers and low-noise receivers for such systems. These improvements have not generally been implemented in systems that operate in or below the HF band, because internal noise at these frequencies is normally of little concern in comparison with environmental noise from external sources. In a nuclear environment, however, external HF noise may be reduced to such a degree that receiver noise may become the limiting factor.

Unfortunately, nuclear effects on HF noise are not evaluated in present system-assessment codes. Although these codes account in considerable detail for the reduction in signal strength following a high-altitude nuclear detonation, the noise level is invariably taken to be that predicted for an ambient environment. Consequently, results from these codes are likely to be excessively conservative--that is, the SNR is likely to be underestimated, in some cases by perhaps several tens of dB. Furthermore, improvements in actual system performance are potentially achievable through design optimization for operation in low-noise environments. Lacking means for determining the specifics of these environments, such improvement cannot presently be assessed.

Estimation of nuclear-induced noise reduction is extremely difficult in the general case because of the large number and geographic extent of potential noise sources. For example, the noise level following a single high-altitude detonation depends strongly on the receiving antenna pattern and on the relative location of the burst with respect to the antenna and the noise sources. However, many simplifications are possible for a severe attack in which the high-altitude radioactive debris extends over a wide region.

This report describes a new and relatively simple approach for estimating the level of external HF noise in severely disturbed environments. The major components of HF noise are identified in Section II, together with a nontechnical discussion of the potential reduction of each type of noise in a nuclear environment. Previous attempts to model the stressed noise environment are briefly summarized in Section III. Section IV describes the proposed new model and gives appropriate equations for its implementation.

II BACKGROUND

In the most general sense, the HF noise environment includes both broadband radio noise and narrowband interference emitted by other users of the HF band. This paper deals only with broadband environmental noise, for which the mean power is assumed to be proportional to bandwidth in any bandwidth that is small, relative to the center frequency. Because the mean noise power is proportional to the effective antenna noise temperature, these parameters can be used interchangeably; antenna temperature is used in the model to be developed in Section IV.

A. Types of Noise Important to HF Systems

In the HF band, environmental noise usually dominates equipmental noise. Environmental noise is broadband interference that enters the receiving antenna along with the signal. While external noise is not unique to HF systems, it is considerably more complex at HF than at higher frequencies. One reason for this difference is the change in character and intensity of noise sources as a function of frequency. Another is the ability of HF noise from distant sources to propagate to the receiving site via the ionosphere.

There are three principal types of environmental noise:

(1) Atmospherics (sferics) from thunderstorms and other types of disturbed weather.

(2) Cosmic (galactic) noise.

(3) Man-made (cultural) noise.

1. Atmospheric Noise

Atmospheric noise is usually the dominant type of noise at HF, especially in the lower portion of the band. It is variable in character and may change over wide limits as a function of location, frequency, bandwidth, time of day, season, solar activity, and azimuthal direction.

It is the source of static, which is familiar to all radio listeners. Atmospheric noise in the HF band can propagate by way of the ionosphere over long distances. Its character thus depends on the distribution of thunderstorms, the noise radiated by each storm, and the efficiency of its propagation. In the presence of local storms, atmospheric noise may be an important factor at almost any frequency, but it is the ability of noise from distant thunderstorms to propagate over long distances that makes it so important at HF and lower frequencies.

Nighttime noise levels are usually high because noise is propagated from distant storms. When ionospheric absorption is high during the daytime, the contribution from distant sources is reduced and local sources become more important. However, because of the strength of propagated noise, the diurnal maximum occurs at night--even for locations in the earth's major noise source regions--although thunderstorm activity is most prevalent during late afternoon.

Noise propagation follows the same pattern as signal propagation. Hence, whenever the signal can propagate, atmospheric noise at the same frequency can likewise propagate over the same path. The noise power available to a directional antenna may be expected to increase when the antenna is directed toward a strong noise source such as a distant thunderstorm center. However, most of the published values of mean noise power are based on measurements with omnidirectional antennas. Although some adjustment is needed to apply these values to the case of a directive antenna, no satisfactory method is presently available to accomplish this adjustment.

2. Cosmic Noise

Cosmic noise is thermal noise that originates outside the earth and its atmosphere. It includes both solar radio noise and noise from interstellar space. Because the sun and other discrete sources (radio stars) subtend very small angles (less than half a degree) at an antenna on the ground, the generalized radiation from the galactic plane is the major constituent except when a highly directional antenna is aimed directly at a "hot spot."

The low-frequency cutoff of cosmic noise is determined by the peak density of the ionosphere; radio waves of frequency less than the critical frequency of the F region cannot penetrate to the earth. Thus, cosmic noise starts to become an important factor near the frequencies where propagated atmospheric noise drops out due to lack of ionospheric support. Except at the highest frequencies and at very quiet receiving sites, cosmic noise is rarely the dominant type of noise for an HF system in the ambient environment.

3. Man-Made Noise

Man-made, or cultural, noise is a composite of noise from many sources. Its principal component in the HF band is radiation from power transmission lines. Automobile ignition systems, fluorescent lamps, and heliarc or RF-stabilized arc welders also radiate HF noise. Man-made noise propagates primarily by the groundwave and along power lines. Thus, its range of effects is limited and its average value depends primarily on the location of the receiving site relative to population centers.

B. Nuclear Effects on Received Noise

Following certain classes of nuclear detonations--namely, those that produce extensive D-region absorption--external noise levels may be substantially reduced, as was observed[1,2] following high-altitude nuclear tests in 1958 and 1962. This is particularly important in the case of atmospheric noise, which propagates from distant thunderstorms to the receiver by ionospheric refraction in much the same manner as the signal. If the disturbance is widespread, the SNR may remain more or less constant despite the increased attenuation until the noise level is reduced to that of the receiving system itself. If the disturbance is limited in extent, either signal or noise may experience the greater attenuation, depending on the particular configuration of propagation paths and absorbing regions.

In contrast, man-made radio noise is typically local in character and therefore is much less affected by changes in the propagation environment. On the other hand, reduction of local man-made noise during the

attack can be anticipated simply as a result of widespread damage and the disruption of normal activity. These effects are not considered in this report.

In such situations, cosmic noise may well become dominant and cannot be ignored. In order to penetrate the F region, this component must arrive by less oblique paths than propagated atmospheric noise at the same frequency. This, and the single (rather than double) traversal of the absorbing region by the cosmic-noise path, cause the cosmic component to decrease less rapidly in intensity with increasing degree of disturbance than does noise from terrestrial sources. This behavior makes cosmic noise potentially important under disturbed conditions, particularly in the upper portion of the HF band--a fact apparently heretofore unrecognized.

Finally, nuclear detonations themselves have been observed to produce three distinct types of radio noise: (1) thermal noise radiated by the hot fireball (2) synchrotron noise emitted by trapped beta particles (from high-altitude bursts) spiraling around the earth's magnetic-field lines, and (3) bremsstrahlung radiation from debris beta particles. These three types of noise are not considered in this report.

III PREVIOUS METHODS OF STRESSED-NOISE ESTIMATION

A. Partial Development of a General Model

During the development of the NUCOM code for predicting performance of HF communication systems in an arbitrary nuclear environment, a method was devised by SRI to predict the reduction in propagated atmospheric noise.[3] The method is completely general in its approach, applying to all degrees of disturbance from ambient to a massive attack. It has the added advantage of predicting the elevation and azimuthal angles of arrival--in other words, the directional characteristics of HF noise, which cannot be estimated by many simpler techniques.

The major areas of thunderstorm activity were postulated for each of four seasons and six time blocks; in the cases tested, seven such sources were found to be adequate to describe the ambient noise environment. The location and power of each source were allowed to vary diurnally, seasonally, and with frequency. Propagation from each source to the receiver was computed by the rapid semianalytic procedure used in NUCOM to determine propagation modes and losses. Ionospheres were generated from the ITS coefficients for normal conditions, and by use of the WEPH code[4] for nuclear conditions. The results for half of the time blocks during the summer (those completed before termination of the project) were in excellent agreement with CCIR median values.[5]

B. A Simple Method of Establishing Bounds on Mean Noise Power

The noise estimates obtained from present HF nuclear-effects codes are clearly upper bounds on the noise in a nuclear environment, because they take no account of the excess losses resulting from nuclear-produced D-region absorption. A simple procedure can be applied to establish a lower bound on the noise, and therefore assess the maximum potential error in noise predictions made with the existing codes.[6]

The maximum potential reduction in noise level produced by nuclear blackout can be estimated directly from CCIR noise maps.[5] Notice, first, that the antenna noise temperature from local thermal sources will be just the environmental temperature. This temperature will be about 290 K if it is assumed that the earth radiates efficiently into a sizable fraction of the antenna field of view. An antenna that views the sky primarily, or which views the radio reflection of the sky in a good conductor (such as the ocean), may see a temperature several tens of degrees lower. This temperature represents, as is discussed in Section IV.A., thermal radiation from a highly absorbing ionospheric D region. The noise values given by CCIR are directly usable to estimate the maximum reduction possible in the external noise since they represent the received noise intensity in the ambient environment relative to a nominal ground temperature. The procedure is illustrated here for two midlatitude receiving sites.

Two representative locations were chosen at which to scale the noise intensity from the CCIR charts--76°W, 39°N, and 100°W, 45°N. The CCIR noise temperatures for these locations at 1 MHz and at 10 MHz are given in Table 1 as functions of season and local time of day (in 4-hour blocks). The intensity relative to thermal ambient can be seen from Table 1 to vary appreciably with these parameters.

The noise level--and therefore the maximum possible reduction as a result of elimination of skywave propagation from remote thunderstorms--is almost always larger at 1 MHz than at 10 MHz; however, reduction of at least 30 dB appears possible in all cases.

This result suggests that SNR estimates, with present codes, may be pessimistic by roughly 30 dB, or more, in a severe nuclear environment. The extent to which such improvement could be realized in actual operations depends on the level of cosmic noise and that of internally generated receiver noise; the latter is not considered here.

Table 1

ATMOSPHERIC-RADIO-NOISE INTENSITY

Season	Time Block (local)	Intensity Relative to 288°K Source (dB)			
		76° W, 39° N		100°W, 45° N	
		f = 1 MHz	f = 10 MHz	f = 1 MHz	f = 10 MHz
Winter	0000	70	35	64	32
	0400	59	33	53	31
	0800	32	32	29	31
	1200	32	34	29	33
	1600	58	39	55	37
	2000	68	40	60	36
Spring	0000	79	43	75	41
	0400	60	40	53	38
	0800	43	33	35	31
	1200	50	34	48	33
	1600	59	42	59	42
	2000	77	45	75	44
Summer	0000	89	47	89	47
	0400	60	39	61	40
	0800	44	31	46	31
	1200	69	37	70	37
	1600	74	46	79	47
	2000	83	47	89	48
Autumn	0000	77	39	75	38
	0400	65	38	60	35
	0800	34	31	32	30
	1200	43	34	38	32
	1600	64	41	62	40
	2000	76	41	75	41

IV THE PROPOSED MODEL

The model described here is appropriate for use in severely disturbed nuclear environments in which high-altitude (above 20 km) radioactive debris is widespread. It is assumed that the receiver is located well within the disturbed region so that ionospherically propagated noise arriving from any direction must penetrate the nuclear-enhanced D region.

The noise in these environments generally is limited by the high absorptive attenuation on sky-wave paths; often, only sources relatively near the receiver remain significant. This restriction simplifies both the modeling necessary to represent the source activity and that necessary to account for propagation losses. Terrestrial noise activity in the source area can usually be adequately represented by that in the immediate vicinity of the receiver. Sky-wave propagation characteristics similarly vary little over the region of interest. Furthermore, only one-hop paths need be considered to represent terrestrial sources beyond ground-wave range. With these simplifications, the calculations necessary to determine the received noise in the disturbed environment, including variation with look direction, become modest.

A. Propagation

Sky-wave high-frequency (HF) propagation in a severe nuclear environment typically is characterized by severe absorptive losses in the D region of the ionosphere. These losses are enhanced above those normally encountered in this region, which can themselves be substantial, by reason of the increased ionization levels that result from both the prompt and debris radiation associated with high-altitude detonations (and, possibly, with large-yield atmospheric detonations). For receiving systems located within the attacked region, the severity of D-region absorption implies a major simplification of sky-wave propagation characteristics. The propagation model developed here to relate received noise to its sources attempts to take full advantage of this circumstance.

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Several factors contribute to simplification of the propagation model. For one, it is possible to limit consideration to propagation modes of no more than one hop. Propagation losses increase with additional reflections from the ionosphere so rapidly that multiple-hop modes contribute negligibly to the net sky temperature in spite of the larger source areas covered by these modes for a given elevation angle of the ray path. We note further that ray paths with higher elevation angles that travel shorter ground ranges generally suffer lower losses than do those that penetrate the D region at more grazing angles. This behavior suggests that sampling the ionosphere at but a single point--namely, that directly above the receiver--may suffice to evaluate the propagation environment.

Ground-wave and line-of-sight propagation paths to the receiving antenna from local noise sources also will be excluded from consideration in the following discussion. A case can be made that lightning sources within line-of-sight or groundwave range of the antenna should provide the dominant contribution to the mean noise power. The volume accessible to the antenna by way of these propagation modes is, however, sufficiently restricted that the probability of occurrence of a lighning discharge within it at any given time can be expected to be small for most locations at most times. Consequently, it is meaningful to address, at least initially, the mean noise level, or antenna temperature, in the absence of local sources.

The antenna noise temperature can generally be expressed as an integral of observed temperature over all look directions. For example, a receiving antenna located on the earth's surface is restricted in view to one hemisphere, and its noise temperature can be written as follows:

$$T_A(f) = \frac{1}{\int_0^{\pi/2} d\theta \sin\theta \int_0^{2\pi} d\varphi \, p(\theta,\varphi)} \int_0^{\pi/2} d\theta \sin\theta \int_0^{2\pi} d\varphi \, p(\theta,\varphi) T_s(\theta,\varphi) \qquad (1)$$

where φ and θ are, respectively, the azimuthal and polar zenith angles that define the look direction, $p(\theta,\varphi)$ is the antenna power gain pattern expressed in terms of these angles, and $T_s(\theta,\varphi)$ is the apparent sky temperature as a function of the look direction. The integration of $p(\theta,\varphi)$ that appears in the denominator on the right-hand side of Eq. (1) allows for the possibility that p may not be normalized so as to make this integral take the value unity. In the case of an elevated receiving antenna (e.g., as for an airborne receiver), the upper limit of the range of θ integration in Eq. (1) would normally be π rather than $\pi/2$.

Several sources of noise can contribute to the sky temperature T_s. Those usually of greatest importance at HF and very-high frequencies (VHF) are (neglecting man-made noise) lightning and cosmic processes. The elevation angles over which these two sources contribute to the antenna noise temperature are essentially mutually exclusive. An abrupt change from one source to the other occurs as the path of the arriving noise shifts from reflection to penetration of the ionosphere. The zenith angle at which this shift occurs depends on the ratio of the operating frequency, f, to the F-region critical frequency, f_c. This angle, denoted θ_c, is given for curved earth by Bouger's rule:

$$r_e \sin\theta_c = r_p \left[1 - \left(\frac{f_c}{f} \right)^2 \right]^{1/2} \tag{2}$$

assuming spherical symmetry. The parameters, r_e and r_p are the radial distances from the earth's center to the receiver and to the peak of the F region electron-density profile, respectively.

The apparent sky temperature observed by the antenna is reduced by propagation losses. These losses also imply that the absorbing medium responsible for them is itself radiating thermally. Although this radiation is normally not significant, the high losses in severe nuclear environments suggest that it may in this case set the lower limit of antenna noise. If T_o is the effective source temperature in the absence

of losses and T_m is the temperature of the absorbing region, then the apparent sky temperature, T_s of Eq. (1), can be written:

$$T_s = 10^{-L/10}\, T_o + (1 - 10^{-L/10})\, T_m \qquad (3)$$

where L is the absorptive loss, in dB, that results from propagation through the region. If the temperature of the absorbing region is not uniform, Eq. (3) becomes an integration of the incremental loss along the path, but such elaboration is not really necessary here. The D region of the ionosphere, in which the bulk of our propagation losses are encountered, normally has a temperature the order of, but somewhat less than, that of the ground. Eq. (3) implies that this temperature constitutes a lower limit to the antenna temperature in the presence of high propagation losses.

The loss L generally depends on the propagation path, and even for a uniform ionosphere this loss will be a function of the polar angle θ. Additionally, lightning noise in being reflected by the ionosphere suffers loss on both the upgoing and the downgoing legs of its path. If L is defined to be the one-way path loss, then the insertion of Eq. (3) into Eq. (1) consequently yields, for a ground-based receiving antenna:

$$\begin{aligned} T_A(f) = \frac{1}{\int d\varphi \int d\theta \sin\theta p} \Bigg\{ & \int_0^{2\pi} d\varphi \int_0^{\theta_c(f)} d\theta \sin\theta p(\theta,\varphi) \\ & \cdot \Big[10^{-L(\theta,\varphi)/10}\, T_c(\theta,\varphi) \\ & + (1 - 10^{-L(\theta,\varphi)/10})\, T_m \Big] \\ & + \int_{\theta_c(f)}^{\pi/2} d\theta \sin\theta\, p(\theta,\varphi) \\ & \cdot \Big[10^{-L(\theta,\varphi)/5}\, T_L(\theta,\varphi) \\ & + (1 - 10^{-L(\theta,\varphi)/5})\, T_m \Big] \Bigg\} \end{aligned} \qquad (4)$$

where T_c and T_L are the effective temperatures of the cosmic (galactic) and the lightning noise sources, respectively and, as before, T_m is the D-region radiative temperature.

As noted above, large propagation losses within an area undergoing a severe nuclear attack, by limiting the size of the region from which lightning noise can be received, make reasonable the assumption that lightning source and propagation characteristics are uniform about the receiving site. The major implication of this simplification for Eq. (4) is that all quantities except the antenna pattern, p, and the galactic source, T_c, become independent of the azimuthal angle φ. Thus, we may write:

$$T_A(f) = \frac{1}{\int d\theta \sin\theta \int d\varphi p} \Bigg\{ \int_0^{\theta_c(f)} d\theta \sin\theta \left[10^{-L(\theta)/10} \int_0^{2\pi} d\varphi p(\theta,\varphi) T_c(\theta,\varphi) + \left(1-10^{-L(\theta)/10}\right) T_m \int_0^{2\pi} d\varphi p(\theta,\varphi) \right]$$

$$+ \int_{\theta_c(f)}^{\pi/2} d\theta \sin\theta \left[10^{-L(\theta)/5}\, T_L(\theta) + \left(1-10^{-L(\theta)/5}\right) T_m \right] \cdot \int_0^{2\pi} d\varphi p(\theta,\varphi) \Bigg\} \; . \tag{5}$$

A substantial further reduction can be achieved in the information needed to determine the antenna temperature by noting that propagation losses for the most part occur in the D region. This region is sufficiently thin that a given oblique path through it has nearly a constant angle to the vertical. The loss on the oblique path is consequently related to that on a vertical path simply by writing:

$$L(\theta_o) = L_v \sec\theta_o \tag{6}$$

where θ_o is the angle to the vertical of the path at D-region height.

Finally, the rapidly increasing propagation losses encountered with increasing θ, as noted previously, constrain the major contributions to the antenna temperature to moderate angles. For these angles, a planar approximation to the earth-ionosphere geometry suffices. In this approximation, Eq. (3), which gives the angle θ_c at which the source shifts from lightning to galactic, simplifies to:

$$\sin \theta_c = \left[1 - \left(\frac{f_c}{f}\right)^2\right]^{1/2} . \tag{7}$$

In this approximation the angle θ_o at which the path traverses the D region also equals the look angle θ at the receiving antenna. With these simplifications, Eq. (5) takes the form:

$$\begin{aligned} T_A(f) = \frac{1}{\int d\theta \sin\theta \int d\varphi P} \Bigg\{ & \int_0^{\theta_c(f)} d\theta \sin\theta \left[10^{-L_V \sec\theta/10} \int_0^{2\pi} d\varphi P(\theta,\varphi) T_c(\theta,\varphi) \right. \\ & \left. + \left(1 - 10^{-L_V \sec\theta/10}\right) T_m \int_0^{2\pi} d\varphi P(\theta,\varphi)\right] \\ & + \int_{\theta_o(f)}^{\pi/2} d\theta \sin\theta \left[10^{-L_V \sec\theta/5}\, T_L(\theta) \right. \\ & \left. + \left(1 - 10^{-L_V \sec\theta/5}\right) T_m\right] \\ & \cdot \int_0^{2\pi} d\varphi P(\theta,\varphi) \Bigg\} . \end{aligned} \tag{8}$$

Equation (8) is remarkable in the minimal demand that it makes for propagation information. Only the one-way vertical absorption and the F-region critical frequency, evaluated at the receiver location, are needed. These quantities are readily obtained from presently available

nuclear-environment/HF propagation codes. The only other quantities required to determine the antenna temperature are the antenna pattern and models (discussed in the next section) for T_c and T_L. The calculation is sufficiently simple, even including a dependence of galactic noise on look angle, that the computational load should be insignificant compared to that required to evaluate signal propagation behavior.

As a next approximation, the sampling of L_v at several ionospheric points, at different azimuths surrounding the receiver location, could be introduced without much alteration of the model. Azimuthal variations in lightning activity could also be incorporated into the model at this stage. Variations of L_v and T_L with distance from the receiving point cannot, however, be taken into account without elaboration of the propagation model to relate elevation angle to ground range.

B. Sources

Noise sources are most conveniently characterized, in the absence of propagation effects, by their effective noise temperatures. This characterization is standard for cosmic noise, which is a major contributor to the total received noise at very-high frequencies (VHF) and in portions of the HF range. However, the other major noise source considered here, the lightning discharge, is not normally characterized in such terms.

The conversion of available information on lightning activity into the form of effective source temperature is the major task addressed in this section.

1. Lightning Noise

Several models of lightning as a global source of HF radio noise have been developed. Surprisingly few discrete radiators, chosen to represent major centers of thunder activity, provide an adequate representation under normal conditions or in the presence of a weak or spatially limited propagation disturbance.[2,3] Better suited to our needs, however, is the model developed by Ortenberger et al.,[7] in which the hourly probability of thunderstorm occurrence has been related to the power radiated per unit area of the earth's surface. Conversion of this

result to a relationship between effective source temperature and probability of thunderstorm occurrence is straightforward in principle. Unfortunately, the description provided by Ortenberger et al. of their analysis is not sufficiently detailed to accomplish this step without some further elaboration.

The use of thunderstorm occurrence probability as a measure of lightning activity has some deficiencies. Principally, it fails to take into account variations of lightning activity within storms or storm complexes as a function of their intensity or rate of occurrence. This difficulty can be alleviated by the use of lightning flash rate as the basic descriptor of source activity.[8] Preliminary work along these lines shows some promise of success. What is required is a relationship between the statistics of lightning occurrence, as represented by the rate of flashes per unit area, and T_L. Such a relationship can be established by comparison of antenna noise temperatures, calculated using Eq. (5), with those given by standard charts[5] under conditions for which the model assumptions might reasonably be expected to be valid--namely at times for which ambient propagation losses are high. Alternatively, it may be feasible to unfold the work of Ortenberger et al.[7] so that their results provide the desired scaling relationship, since both representations ultimately depend on the thunderstorm-day statistic as a measure of source activity.

First, however, it is necessary to note that T_L is not directly related to lightning-flash rate. As a noise source, lightning discharges are sparse and sporadic. Consequently, the effective temperature of the volume they occupy, which constitutes a thin horizontal sheet located near the earth's surface, depends on the elevation angle at which this sheet is viewed. If T_D is taken to be the effective surface temperature of a lightning discharge channel, T_L can be written:

$$T_L = (1 - e^{-\mu \ell})T_D \quad , \qquad (9)$$

where ℓ is the slant distance of a path through the source region. The factor μ is a loss rate that in effect describes the probability that a signal passing along this path will encounter a discharge channel. If the source region is taken to have a vertical thickness h, Eq. (9) can be written:

$$T_L = (1 - e^{-\mu h \sec \theta}) T_D \quad . \tag{10}$$

As represented by Eq. (10), two parameters characterize the lightning source, namely, T_D and the product μh. High D-region absorption at low elevation angles limits the significant source areas, however, to elevation angles for which $\mu h \sec \theta$ is small (cf. the discussion in Section IV-A). Consequently, Eq. (10) can be simplified to read:

$$T_L \approx \mu h T_D \sec \theta \tag{11}$$

before substitution into Eq. (8). In this form, the quantity $\mu h T_D$ can be assumed to be proportional to lightning-flash rate.

A preliminary evaluation, ignoring the obliquity at which the lightning-source region is viewed, was performed to obtain a relationship between T_L and lightning-flash rate averaged over θ. This relationship is summarized by the expression

$$\overline{T_L} = \alpha \sigma_h \quad , \tag{12}$$

where σ_h is the number of flashes per square kilometer per hour and α was found to have the value:

$$\alpha = 1 \times 10^{14} \, f_{MHz}^{-3.64} \; K \cdot km^2 \cdot h \quad . \tag{13}$$

This result should be refined to relate μhT_D to σ_h without averaging over θ before incorporation into a final model.

2. Cosmic Noise

Cosmic noise is a subject of considerable complexity. The level of detail needed in our application is, however, not great, and much simplification consequently is possible. A useful expression for the sky temperature, T_c, that results from cosmic sources is:

$$T_c = 100\ \lambda^{2.3}\ K \quad , \tag{14}$$

where λ is the radio wavelength, in meters. This expression represents an average over look directions for an antenna with little directivity.[5] Sky temperature varies by about an order of magnitude at HF as a function of look direction, with a maximum toward the galactic center and minima toward the galactic poles.[9] Broadbeam antennas normally will average over this variation, and even a fixed (in earth coordinates) directive antenna generally will sample different regions of the sky at different times. Neglect of this variability consequently seems a reasonable first approximation. Elaboration of the model to describe the broad variation of sky temperature with look direction would, however, be a useful and not difficult improvement.

V SUMMARY

The model developed in Section IV is capable of describing the natural noise environment under conditions of severe propagation disturbance. The model is of a form readily implemented computationally. The information on propagation characteristics required by the model is minimal and is readily available from present nuclear-environment codes.[10] Implementation of the source components of the model would require inclusion in some form of a global representation of lightning activity. The preferable representation would be in terms of lightning-flash density, but probability of thunderstorm occurrence, which might require less effort to implement, would also serve adequately.

Completion of the noise model described by Nielson et al.[3] could complement the model developed here by providing a capability to treat less severe, or localized, propagation disturbances. Considerable progress has been achieved in the description of lightning as a source of radio noise since their work was performed. These accomplishments would greatly simplify the task of completing this model.

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